FUNCTIONAL ELECTRICAL THERAPY SYSTEMS: NEUROPROSTHESES FOR LIFE-LIKE REACH AND GRASP

Popovic B. Dejan♣, Popovic B. Mirjana♣,♠, Fisekovic Nebojsa♦, Sinkjaer Thomas♣

♣Center for Sensory Motor Interaction, Aalborg University, Denmark; ♠Institute for Medical Research, Belgrade, Yugoslavia; ♦Phillips, Eindhoven, The Netherlands

Abstract-**A programmable multi-channel neuroprosthesis for functional electrical therapy was developed. This research follows the neurorehabilitation studies indicating that the provision of life-like reaching and grasping in stroke subjects is essential for their faster and more effective recovery. The designed 16-channel neuroprosthesis delivers charge-balanced impulses, and controls the pulse width, frequency and stimulus intensity on each channel independently. The main novelty is a controller that supports sensory driven, rule-based control. The rules use sensory information and mappings that can be determined by machine learning. The controller supports up to eight analog sensors, six digital sensors, five timers, and comprises a flash memory for handling time series. An interface for downloading programs from a PC computer was realized *via* a serial communication channel by means of an infrared link.**

Keywords – **Neuroprosthesis, therapy, reaching, grasping**

I. INTRODUCTION

Functional electrical stimulation systems are a suitable assist for reaching and grasping in humans with stroke or spinal cord injury [9]. Several electronic stimulators have been developed and tested in neuroprostheses that aim to provide reaching and grasping [9]. Following the findings in the field of functional electrical stimulation (FES) a programmable eight channel surface stimulator has been developed based on a Motorola 68HC11 microcontroller (μCo) and the implementation of a switch-mode power supply. This stimulator has eight programmable stimulation channels and it is fully portable [7]. Another programmable stimulator that uses Motorola 68HC11 μCo was designed with the following features: four channels, charge compensated monophasic stimulation pulses, fully controllable stimulation pattern was effectively tested for control of standing and walking. The galvanic isolation of each of the channels and the possibility to simultaneously use more then one stimulator in a master-slave mode were the most important innovations [3]. A modified and improved version of the stimulator designed by Ilic *et al.* [3] integrates amplifiers to be used in the EMG-triggered mode of operation and the appropriate artifact blanking circuitry [14]. Brown *et al.* [1] developed a μCo-based eight-channel distributed muscle stimulator that can adjust stimulation timing to produce smooth tension over a range of stimulus rates. This design was based on modeling results. The experiments performed on skeletal muscles showed that this system can reduce fatigue, having important implications in FES.

An implantable integrated stimulator and telemetry system was developed and presented by Smith *et al.* [15].

This system is able to fulfill the stimulus and telemetry needs of advanced FES applications requiring multiple channels of stimulation and multiple channels of sensor or biopotential recordings. This system provides a command control structure, an inductive radio frequency link for power to the implant device, a two-way transcutaneous communication, an interface for decoding the command signals, and modular circuitry providing the specific implant functions.

A direct-synthesized arbitrary waveform stimulator for multichannel stimulation was described by Wu *et al.* [16]. A digital signal processor implemented an "element-envelope" method; it synthesized the required stimulating patterns with high resolution. This method reduces the memory requirements, and it preserves the ability to adjust stimulation parameters dynamically. Lin *et al.* [4] have developed a low cost, programmable, galvanically isolated bipolar eight-channel stimulator. The design was based on a TMS320C31 DSP-chip. The DSP chip generates a wide range of either arbitrary current waves or biphasic current pulses. The DSP-based stimulator can process the stimulated electromyographic (EMG) signal simultaneously, or some other sensory signals. A user-friendly interface for programming of the stimulator has been developed for the host computer, using Windows environment and a push-button control for functional application of the system.

Functional electrical therapy, that is the use of a neuroprosthesis for providing movement in stroke subjects contributes to the recovery of movement in stroke subjects [10]. In one of the earliest FES studies Merletti *et al.* [5] used a two channel electrical stimulator to augment elbow extension and grasping. The device used proportional control, and it allowed independent control of each of the stimulation channels. The conclusions were that FES improved both the hand and elbow movements. Nathan [6] described the Handmaster NMS-1® three-channel FES system that contributes to the motor recovery in stroke subjects. The system uses a preprogrammed sequence of stimulation that is switch triggered. Handmaster NMS-1 is now used in several clinical trials analyzing carry-over effects in stroke population. Popovic et *al.* [8] showed carry-over effects of the Bionic Glove® [13] and the Belgrade Grasping System (BGS) [12] in tetraplegic subjects. The results from the study in stroke subjects with the BGS indicate that functional electrical therapy of distal muscles of the paralyzed or paretic arm greatly promotes the recovery of reaching and grasping [10], yet the clinical work clearly indicated that the FES is more effective if proximal joints are also activated. Therefore, we designed a more complex neuroprosthesis that can control

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Abstract

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elbow, wrist and hand, and possibly some degrees of freedom in the shoulder joint in a life-like manner [2].

II. FUNCTIONAL ELECTRICAL THERAPY (FET)

We hypothesized that mimicking life-like synergy for activating upper extremities is the most appropriate strategy for functional electrical therapy (FET) in stroke subjects. This hypothesis is based on the model shown in Fig. 1 promoting the following: 1) FET stimulates afferent pathways, thereby promote very strong sensory input to the central nervous system, and 2) FET activates efferent pathway (motoneurons), thereby muscles that connect to these pathways contract. The contraction contributes to a movement or change of the force in the muscle; thus, activity of muscle afferents is triggered. The movement causes the activity of exteroceptive sensors (e.g., skin receptors). The sensory (afferent) signals are superimposed to very strong signals generated directly by the
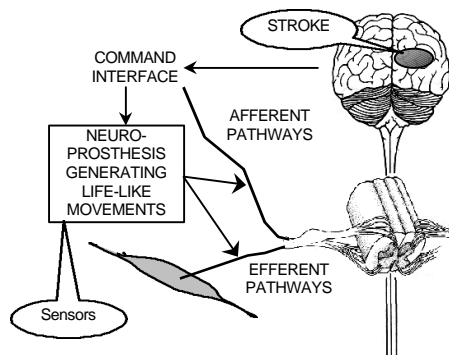

Fig. 1: Functional electrical therapy system. Neuroprosthesis is a multichannel electronic stimulator with rule-based control, and analog and digital sensors.

functional electrical stimulation. In parallel, the activity of paralyzed muscles *per se* contribute to the awareness of the subject that he/she could do things that were not achievable without the FET.

In presence of externally activated function (e.g., grasp), the preserved, but not used mechanisms are voluntarily activated (e.g., shoulder and elbow movement). In this way the functional electrical stimulation of distal muscles promotes extensive activity of proximal muscles leading most likely to even more important development of new control schemes. In addition, the externally elicited movement provides visual feedback, since the subject becomes aware of the movement that he/she was not able to do without the assistive system. The suggested model for FET assumes that the extensive exercise and activation of complex systems will result with the changes of the central nervous system substrate, thus leading to faster and better recovery.

III. FETS - A NOVEL NEUROPROSTHESIS

The Functional Electrical Therapy System (FETS) comprises 16 stimulation channels [2]. The interpulse interval can be set to the interval between 10 ms and 2,55 seconds in increments of 10 ms. The pulse duration can be programmed to be between 10 ìs and 1270 ìs in increments of 10 ìs. The increase and decrease rates of pulse duration are programmable for each of the channels independently. The stimulus intensity can be set between 0 and 65 mA. The power generator (fly-back based DC/DC converter) and output stages (constant current sources) of this novel FETS are improved designs described in details elsewhere [3].

The main operation mode is to assist functional movement of upper extremities, and stimulate afferent pathways, thereby promote very strong sensory input to the central nervous system. In this sensory-driven mode, data from analog sensors are fed to an 8-bit A/D converter, and the digital signals from sensors go directly to a port on the micro-controller (Fig. 2). The controller supports up to a maximum of 6 digital and 8 analog sensors between 0 and 5 Volts. Five fully retriggerable timers are integrated in the controller in order to enable the use of a time series of sensory data and special commands. In order to increase the control capacity five internal control signals can be generated and stored in the flash memory. These control signals define the state of the neuroprosthesis and allow multi-modal operation, that is different stimulation patterns can be activated for the same sensory input. The timers and control signal are important specifically for the application of a hierarchical hybrid rule-based control [9].

Hardware. The controller comprises a μCo, programmable logic arrays (PGA), a flash memory (FM), an infrared (IR) communication port, and a time base generator (TBG). The Motorola MC68HC11 μCo is the core of the device (Fig. 1). The μCo digitizes input signals from analog sensors, receives digital signals, generates part of the address for access to the flash memory, and forwards the appropriate data to the programmable logic arrays. Two PGA (Xilinx XC3042) perform logic operations. These chips generate pulses with defined duration on the basis of information received from the micro-controller and clock generator. PGA chips deal with the logic for the bus control, access to the peripherals and memory modules, and serve as the interface for the digital sensors. FM (Intel, DA28F016SV, capacity 2 MB) was selected since the reading is the same as reading SRAM with respect speed and access, yet the content remains in the memory after the system is switched off. The IR communication was selected for transmission of the control algorithm (generated at a PC computer) to the neuroprosthesis. The IR communication system comprises an infrared transceiver (MINI SIR, Novalog), and the pulse shaping circuit (IC transceiver driver, TOIM3232, Temic). The TBG (LMC555) simplifies the pulse generation and it runs at 100 kHz, ensuring a minimum pulse width of 10 μs.

The interface program for entering the control algorithm and its parameters is supported by Windows 9x operating systems. The menu enables selecting one of the following seven program activities: 1) *Configuration,* 2) *Algorithm definition,* 3) *Program file,* 4) *Stimulator code generator,* 5) *Load,* 6) *Save,* and 7) *Exit*. *Configuration* is used to define active A/D channels and their range, timers and control
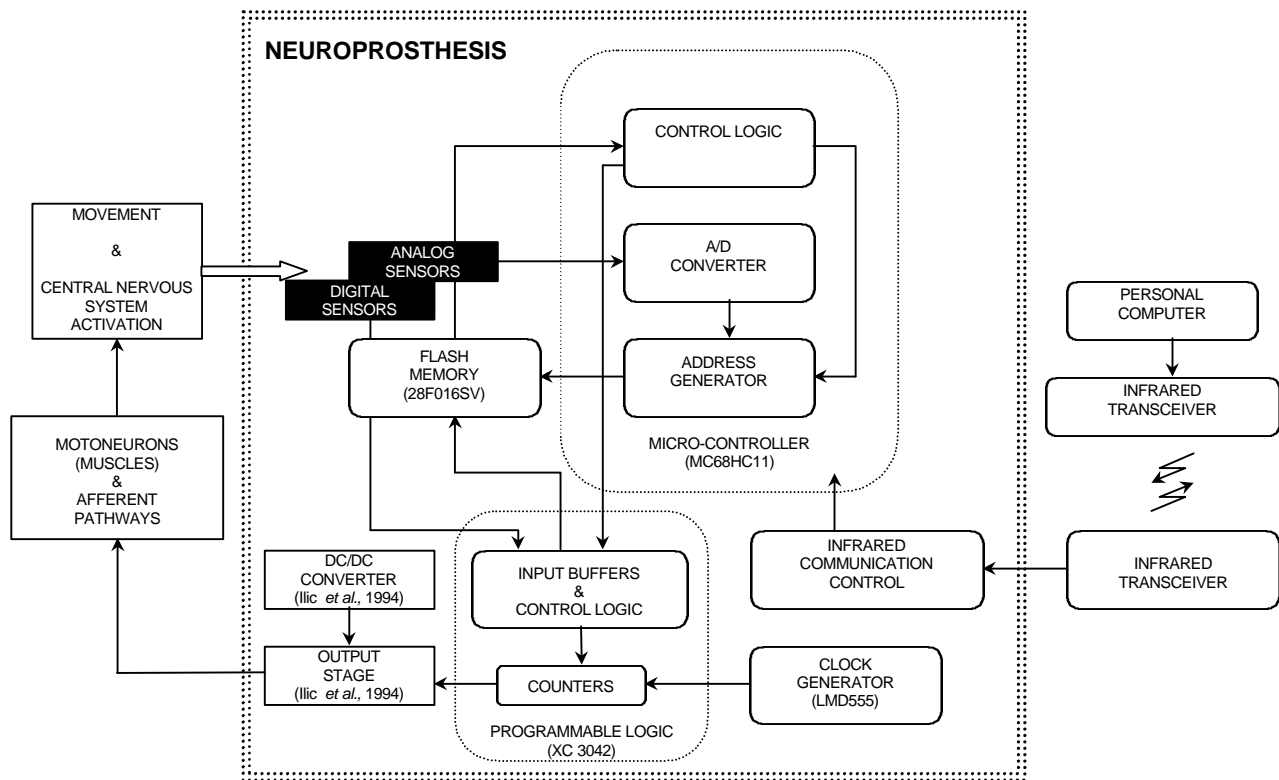
Fig.2: General scheme of the neuroprosthesis for functional electrical therapy.

signals that will be used, number of channels that will be used, and regime of stimulation. *Algorithm definition* is the main part of the program allowing the programmer to define the conditions and appropriate modalities of stimulation. The programmer sets the minimum, maximum, rise, and fall times of pulses for each channel independently, and sets-up the interpulse intervals. The algorithm is automatically downloaded from the machine learning program for functional movement [9]. *Program file* offers two functions. *Condition check* examines whether there are contradictions in the control algorithm (e.g., more than one pattern of stimulation is defined for the same set of input parameters). If contradictory conditions are detected, the program informs the user about the conditions that are contradictory, and they have to be manually corrected. *Stimulator code generator* creates a file containing data formatted appropriately to the micro-controller. *Stimulator load* is used for transferring the file from a PC computer to the micro-controller memory. *Save* allows the programmer to store the defined program on a PC computer for later use. *Exit* closes the programming sequence and prompts the programmer to the unsaved information before exiting.

Control paradigm. The reach/ grasp/ manipulate/ release function is complex dynamic process comprising the planning and execution. The planning of arm movements in stroke subjects remains intact, yet the execution is greatly compromised. The execution involves the hand transport, prehension, grasping, using of the object, and returning and releasing the object at the post. This task is frequently

accompanied with postural adjustments (trunk movement). Ultimately, in order to generate life-like movement it is essential to apply artificial biological-like synergies that would work irrespective of the location, orientation in the workspace, the shape, and the inertial properties of an arbitrary object to be handled. The general scheme of the control is shown in Fig. 3.

The synergies of the dynamic process could be expressed in different space coordinates: we selected to use the angular velocities of the arm segments. In earlier studies [11] the shoulder volitional motion was used as input; the outputs were the stimulation patterns for the elbow flexor and extensor muscles. The scaling synergy was shown inadequate; therefore nonlinear mapping was determined by using artificial neural network [12]. In a comprehensive study in progress we hypothesized that there is a decoupling between the reaching and grasping control in terms of the decision and actuators, yet the timing between these two synergies is critical for function (Fig. 3).

We determined significant coupling of joint flexion/extension angular velocities between involved two arms' neighboring joints (shoulder and elbow) that occurs in the common plane of both motions and prepared the data sets for machine learning that generates rules for the FETS. We also determined synergistic timing between the reaching and grasping functions; these elements are now used with neural networks in order to generate rule-based control.
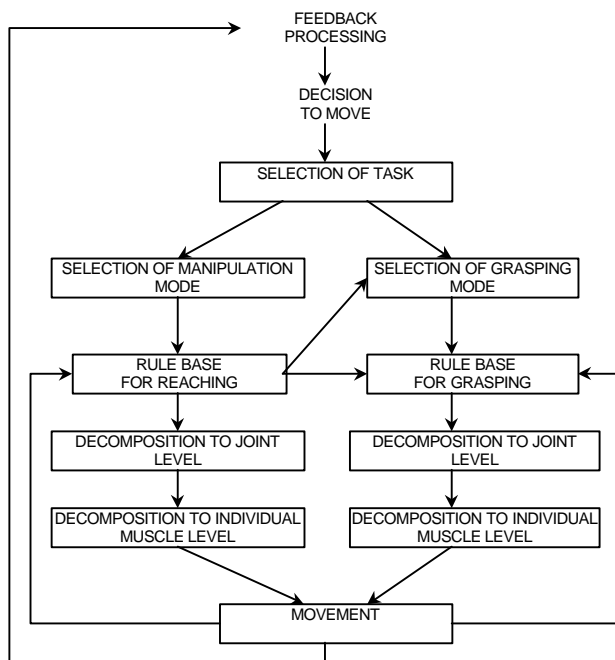
Fig. 3: The organization of the rule-based controller mimicking life-like movements. The rules for reaching and grasping are determined by artificial neural networks using velocity space representation of typical daily activities processed from data collected in able-bodied subjects.

IV. CONCLUSIONS

The designed FETS is simple to use and effective for implementing relatively complex sampled-data sensory driven control algorithm. This system allows adjustments of all the parameters as well as inclusion of new rules off-line, yet during a single clinical session. A therapist was trained to use the PC program and introduce changes of the stimulation sequence during the implementation of the FETS in about 30 minutes. The IR communication channel was shown to work efficiently for modifying of the parameters, yet slow for downloading the whole program. The novel FETS could be applied for neurorehabilitation of humans with lesions of the central nervous system, but also as an orthosis.

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